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SECULAR FLUCTUATIONS IN VULNERABILITY TO TROPICAL CYCLONES IN AND OFF NEW ENGLAND

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ABSTRACT

Paths assumed by tropical cyclones in different fall seasons are related to the form of the prevailing mid-tropospheric general circulation. It is inferred that areas of vulnerability or invulnerability to these storms seem to be prescribed by the climatologically preferred circulation pattern during a given year, and for this reason expanded research along these lines could be highly rewarding. There is some indication that since the mid-thirties general circulation patterns have made east coast areas more vulnerable than during earlier years of the century.

1. INTRODUCTION

In two earlier papers [1, 2] the author discussed some of the long-range factors affecting the genesis and path of tropical cyclones. Coming shortly after the unwelcome visitations to northeastern United States of the damaging trio of hurricanes Carol, Edna, and Hazel, these reports excited considerable public interest. It is the purpose of this report to relate more specifically tropical cyclone occurrences in and just off New England to time-averaged climatic patterns of the general circulation of the order of a season. If such a connection exists, the problem popularly referred to as "hurricane cycles" becomes inextricably linked with the more general problem of climatic fluctuations.

For many years it has been known that the course of tropical cyclones is strongly influenced by the great centers of action. In a climatological sense the general recurvature of tropical storms in a path often resembling a parabola has been associated with the shape of the isobars around the western periphery of the subtropical anticyclones. Since the routine introduction of upper air charts in weather forecasting a number of studies have been carried on relating the motion of hurricanes to the broad-scale flow at one or more elevations in an attempt to find "the steering level." While attempts in this direction cannot be said to have been highly successful, the evidence clearly indicates a pronounced tendency for hurricane movement to be in the general direction of the broad-scale mid-tropospheric current in which the vortices are embedded. If the large-scale atmospheric flow patterns possess a mode then it becomes likely that any tropical cyclones which form and become embedded in this particular pattern will tend to follow a general preferred path. It has been recognized for almost a century that the great centers of action in the sea level pressure field undergo large variations from month to month, from season to season, and from year to year. Corresponding variations in the upper level components (ridges and troughs) of the planetary waves have more recently been demonstrated [3]. Inasmuch as the behavior of tropical cyclones appears to be explained somewhat more rationally and easily on the basis of upper air rather than sea level maps, it seems desirable to explore shorter period climatic fluctuations in these storms with time-averaged upper level charts. If the period of averaging is long, like a month or season, it becomes highly unlikely that hurricanes, which are few in number and small in extent, would materially influence the mean patterns.

Unfortunately, the file of adequate upper air charts for months or seasons is restricted to the short period dating back to 1933. In the last fifteen years or so the source of this material has been conveniently available through readings made twice daily from routinely-prepared 700-mb. hemispheric analyses. These readings are interpolated at points of a close grid from contours, and then punched on cards, thereby facilitating the computation of means. In the decade of the 1930's other methods had to be used in order to extend the charts over ocean areas where very few direct upper air observations were available. Essentially the method employed consisted of: (1) constructing a mean sea level map for the desired period; (2) computing, plotting, and analyzing the field of anomalies (departures from the long-period normal) of these maps; (3) estimating from the anomalous components of flow the layer temperature departures (thicknesses) between 1000 and 700 mb.; and (4) computing and analyzing the field of 700-mb. height for a sufficiently close grid of points on the basis of the sea level pressure anomaly and the estimated thicknesses. In spite of some degree of subjectivity introduced by this method, its results are believed to be satisfactory for many climatological studies which require not exact but only approximate accuracy. For example, when the method was tested for the Pacific, Atlantic, and North American areas for four months when real (observed) means were available it was found that the average error was 60 feet, and the error was less than 100 feet 90 percent of the time. Besides, the patterns of the estimated contour surfaces correlated with the observed patterns with a value of 0.98, and the correlations of the departures from normal between the four pairs of computed and observed patterns were 0.77, 0.67, 0.72, and 0.92.

Inasmuch as we wish to study variations in tropical cyclone tracks and particularly the anomalous character of these tracks in certain months, it is helpful to obtain departures from normal of the mean maps. This has been done by subtracting the long-period normal from each of the monthly and seasonal means. The normals had to be determined for each month by different methods for different areas. For a detailed treatment the reader is referred to [4]. A seasonal mean chart and its anomalous pattern appears in figure 7.

The data for tropical storms were extracted from cyclone track charts published in the *Monthly Weather Review*, supplemented by recourse to individual weather maps when necessary.

2. THE GENERAL RELATIONSHIP BETWEEN PREFERRED PATHS OF TROPICAL CYCLONES AND SEASONAL PATTERNS OF THE GENERAL CIRCULATION

Year-to-year fluctuations in the number of tropical storms are well recognized. Tannehill [5], for example, displays a diagram showing the yearly variation in frequency of West Indian tropical cyclones from 1887, in which numbers range from 1 in 1890 to 21 in 1933. Equally interesting is the fact that certain regions are

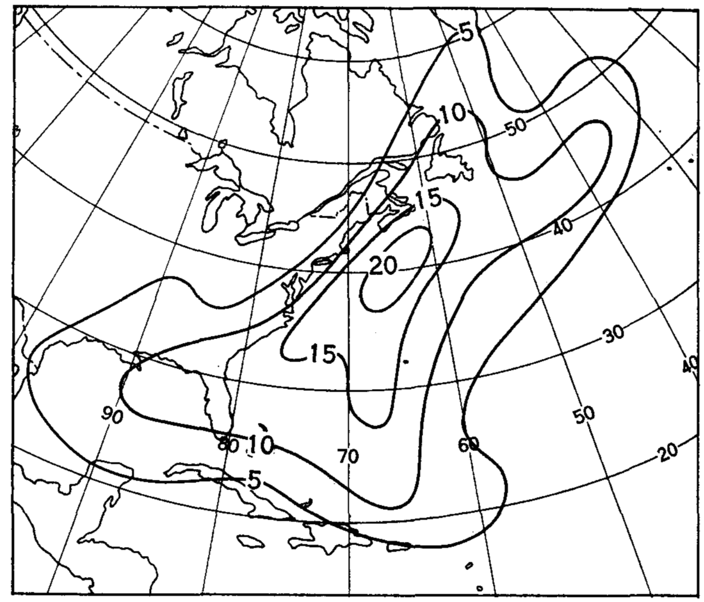

FIGURE 1.—Isopleths showing the number of tropical storm tracks entering 5° squares during the Septembers of 1935–1954.

relatively free of tropical cyclones during some autumns while other regions become unusually vulnerable. An extreme example of this kind is provided by the hurricane season of 1954 when these storms evaded southeastern United States but plagued the Northeast. It is unlikely that these year-to-year variations in number and path are random, particularly since the form and geographical placement of the planetary waves undergo great variations from one hurricane season to another. These varying patterns could set the stage for developing or inhibiting tropical cyclone formation and also for steering these storms once they are formed. A suggestion relating the climatic conditions to tropical cyclone formation was offered in an earlier article [1]. In the present paper however, the path-determining aspects will be the primary topic.

During the past twenty years tropical storms have traversed a broad domain covering eastern United States and the adjacent oceanic areas. From individual paths of these storms during the Septembers of 1935–1954 the number of storms affecting each 5° square has been plotted and analyzed in figure 1. The axes of maximum frequency (which are not necessarily most frequent paths) suggest that during this period the area around 40° N., 65° W. appears to have been the most vulnerable. Storms passing west of here are threats to New England, while those to the east are more likely to be misses. A criterion of vulnerability of the Northeast and adjacent waters was therefore set up according to the number of tropical cyclones in a given month which passed east of 40° N., 65° W. or were observed to pass to the west of this point (or through the point). The Appalachians were taken as a western boundary, and 40° W. as the eastern boundary of the area under consideration. During the Septembers

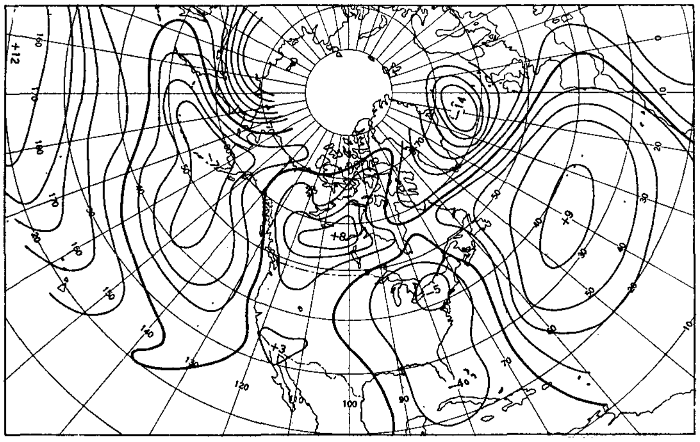

Figure 2.—Composite chart of the average departures from normal (in tens of feet) of 700-mb. height for those seven fall seasons (Sept., Oct., Nov.) of maximum tropical cyclone threat to New England (when three tropical storms moved west of 65° W. at 40° N. in September and October).

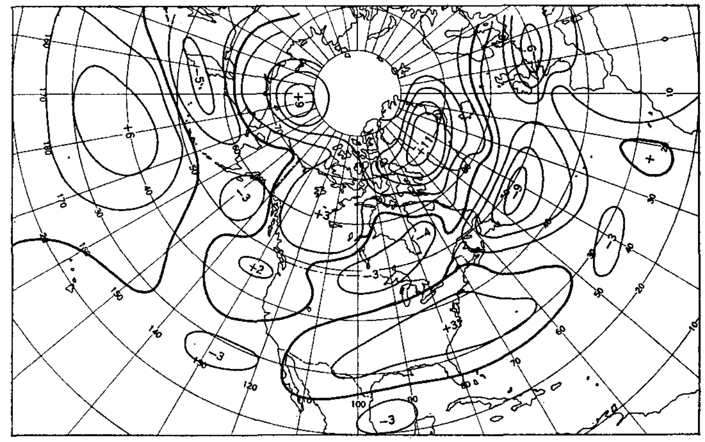

Figure 3.—Composite chart of the average departures from normal (in tens of feet) of 700-mb. height for those six fall seasons when no tropical storms threatened New England.

and Octobers of the years 1933–1954 the number of tropical cyclones which fitted into the latter category (threats to New England) is shown in table 1.

From the table it is apparent that during the falls of 1933, 1934, 1936, 1937, 1938, 1953, and 1954 tropical storms must have worried New England forecasters, while during the falls of 1939, 1941, 1947, 1949, 1951, and 1952 no major problems of this sort arose. The former series of years will be termed "maximum threat" years; the latter "minimum threat" years. November has been omitted in this tabulation since in that month tropical storms hardly ever penetrate close enough to New England to pose a threat. It appears that the years of maximum threat tend to occur in clusters, a fact possibly related to year-to-year persistence of general circulation anomalies.

Table 1.—*Tropical cyclones passing west of 40° N., 65° W. in Septembers and Octobers, 1933–1954*

Year	Number	Year	Number
1933	3	1944	2
1934	3	1945	1
1935	1	1946	1
1936	3	1947	0
1937	3	1948	1
1938	3	1949	0
1939	0	1950	1
1940	2	1951	0
1941	0	1952	0
1942	1	1953	3
1943	1	1954	*3

*Includes hurricane Carol which passed August 31.

A composite chart of the departures from normal of the 700-mb. surface for the autumns [1] of the hurricane-threat years is shown in figure 2. This chart is derived from the individual seasonal charts (means of Septembers, Octobers, and Novembers). The inclusion of so much data (21 months) makes it highly unlikely that the pattern of anomaly would be materially affected by tropical storms of these years, which, after all, occur on a small number of days in given regions and occupy a relatively small portion of the map. It is believed, therefore, that the anomalous features of the general circulation shown in figure 2 are associated with basic recurrences of similar large-scale features, and that these features tend to control the paths of the tropical vortices as well as other disturbances. The well-defined character of the anomalous areas in figure 2 is due to persistent recurrence during several seasons. If a smilar map is prepared for the years when no tropical storms threatened, the corresponding pattern (fig. 3), while somewhat less distinctive, also possesses some interesting large-scale features.

Several features of figure 2 are noteworthy. First, the centers of anomaly are extensive, having dimensions roughly of the order of the planetary ridges and troughs which appear on monthly mean charts. Secondly, there appear to be compensations in that large positive anomalies in one area are balanced by negative areas elsewhere. In regard to the problem of hurricane steering, perhaps the first striking item in connection with figure 2 is the negative (−5) anomaly centered just inland from the Atlantic Coast and the associated anomalous southerly component off the Atlantic Seaboard. This is evidently the immediate influence which, once the tropical storm moves northward from the West Indian area, provides for its assumption of a farther westward path than normal after passing Cape Hatteras. Referring to the autumn normal 700-mb. circulation (fig. 4) it is clear that the negative anomaly in effect represents deepening of the trough normally found over eastern United States. During periods of tropical storm threat to New England an amplification of the normal planetary wave pattern occurs, as may be seen by

[1] Seasonal charts were used rather than September-October means because of their availability. In subsequent studies currently contemplated, means of August, September, and October comprising almost the entire hurricane season, will be prepared and studied.

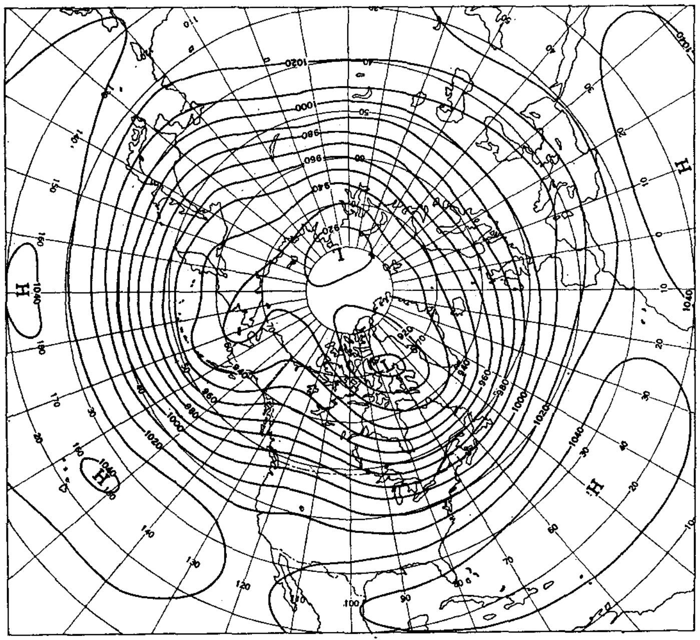

FIGURE 4.—Normal 700-mb. chart for autumn (Sept., Oct., and Nov.). Labeled in tens of feet.

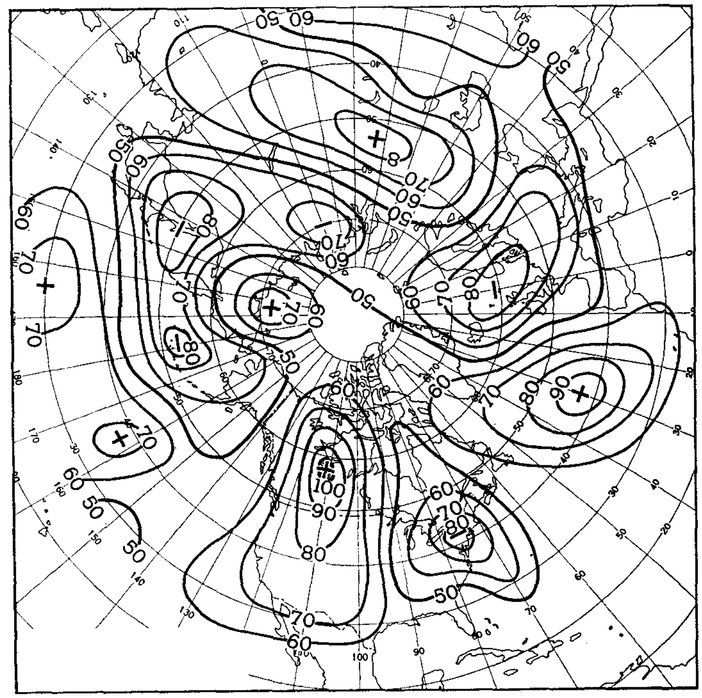

FIGURE 5.—Percentage frequency of sign of 5-day mean 700-mb. height anomaly for all wintertime cases when an axis of maximum positive anomaly lay between 110° W. and 120° W. near 60° N. (From [6].)

superimposing the anomalies of figure 2 on the normal pattern of figure 4. Effectively then, meridional motion of east coast storms, extratropical as well as tropical, becomes favored, making the projecting land areas north of Cape Hatteras more vulnerable.

While the science of meteorology up to now has not been able to explain the ultimate cause of such climatic anomalies as appear in figure 2, considerable knowledge of the interdependence between anomalies in distant portions of the hemisphere has been gained. In fact, one of the best known of these interrelationships, Sir Gilbert Walker's North Atlantic oscillation, where negative anomalies over Iceland usually go with positive anomalies over the Azores, is indicated in figure 2. More extensive work exploring these "teleconnections" for mid-tropospheric levels has been carried on by Martin [6]. Essentially, Martin's work involved dividing several years of 5-day mean 700-mb. maps and anomalies into seasons and stratifying the data so that he could determine the probability of sign of the anomaly in various areas of the hemisphere if one selected area was characterized by a large anomaly (either positive or negative). In a sense his charts may be considered as empirically derived spheres of influence for they incorporate the average influence of differential heating, mountains, and other factors on the flow patterns. Since Martin used selected points 20° of longitude apart for three latitudes (30° N., 40° N., and 50° N.) and two seasons, winter and summer, he obtained a total of 216 charts. One may scan these charts for the key (selection) areas indicated by the anomalous areas in figure 2 in order to see what areas adjacent and remote from the key area would be characterized by large probability centers, and thus make comparison with figure 2.[2] Doing this, one finds that the chart most resembling figure 2 is the one on which the key area is positive and near 60° N. between 110° and 120° W. in winter. This chart is reproduced in figure 5. The similarity in pattern to figure 2 is quite striking, especially with reference to the negative center in eastern United States and the position and orientation of the Atlantic anomalous cells. Other charts selected on the basis of a positive key area for the same longitudes at 50° N. in winter and also for summertime have similarities, but not as pronounced as those of figure 5. At any rate, selecting on the basis of the northwest Canadian area seems to define a pattern most similar to the tropical cyclone threat pattern shown in figure 2. The inference suggested by this correspondence is that the northwestern Canadian area may be one of the key areas to consider in estimating the vulnerability of the Northeast to tropical storms.

Although the above conclusion is based on seasonal means there are shorter-period indications of a similar nature. In the first place, vorticity considerations imply that when the west Canadian ridge builds, its downstream neighboring trough usually deepens—thereby favoring increased southerly flow in its advance which could deflect the course of a captured tropical cyclone. Secondly, any tendency for north to northeast upper level components emanating from the central Canadian region encourages

[2] It can be shown statistically that higher probabilities usually go with higher mean values of the anomaly itself, so that in a general sense, isolines of probability may be interpreted similarly to isolines of anomaly.

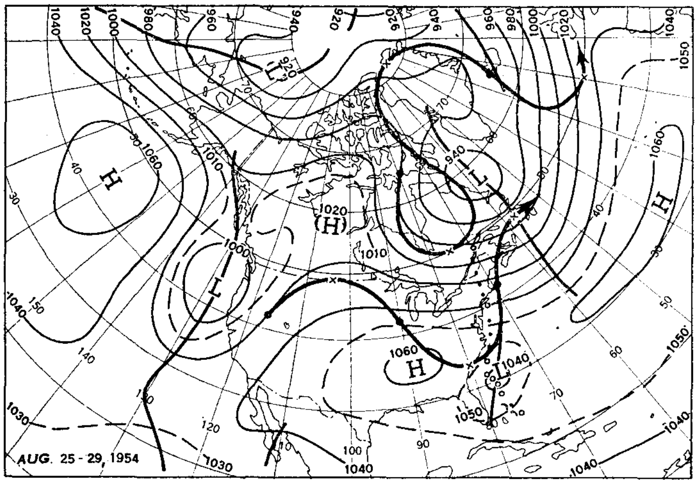

Figure 6.—Five-day mean 700-mb. chart for August 25–29, 1954, immediately preceding penetration of hurricane Carol into New England. Note constant vorticity trajectories (heavy curves) suggesting creation of trough conditions over eastern North America. Path of Carol given by dotted line.

the formation and deepening of troughs in the Great Lakes region, which in turn favors more northward movement of east coast cyclones.

An excellent example of this effect is afforded by hurricane Carol, 1954. In the 5-day period just preceding its northward acceleration (fig. 6) the west Canadian ridge had built up strongly and constant vorticity paths from both north and west sympathetically indicated the formation of a deep trough in and south of the Lake region, which indeed did subsequently form and steered Carol almost due north into New England [7].

It is not meant to imply that the entire general circulation depends on conditions in the west Canadian area, for other "centers of action" are also important. If for some unknown reason the Atlantic anticyclone is weak and the westerlies penetrate strongly into the New England region, tropical cyclones are apt to be steered out to sea without striking land. However, in view of the suggested dependence of other circulations upon a strong positive anomaly over western Canada, a risk factor arises which cannot be dismissed lightly. This risk is of course dependent on the existence of tropical storms which may be captured by the deep polar trough. From the extension of the eastern United States negative anomaly well into the tropics (fig. 2) it appears that this average threat pattern also favors genesis of tropical storms. Such a favorable climate for hurricane genesis may be brought about in the manner suggested in the earlier report [1] i. e., by creating large areas of static instability and general cyclonic vorticity at the base of deep polar troughs.

An example of an individual seasonal pattern of maximum threat (1937) is shown in figure 7. It was indeed fortunate that the hurricanes glanced off New England without striking land, although in the following year when a similar but more aggravated pattern occurred, the great hurricane of 1938 struck.

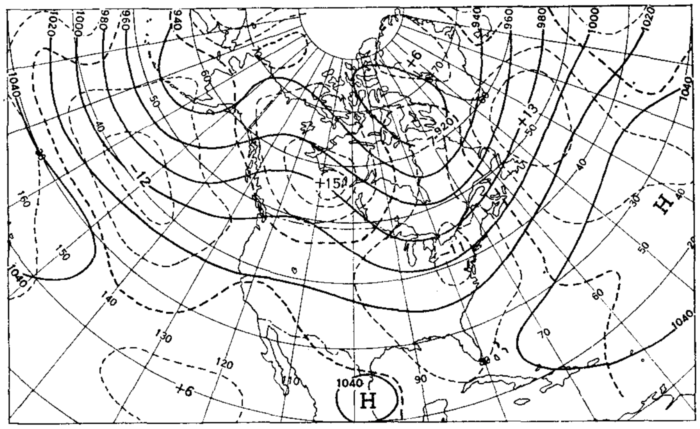

Figure 7.—Mean 700-mb. contours (solid lines) and anomalies (broken lines) for autumn 1937, a maximum threat pattern for the Northeast.

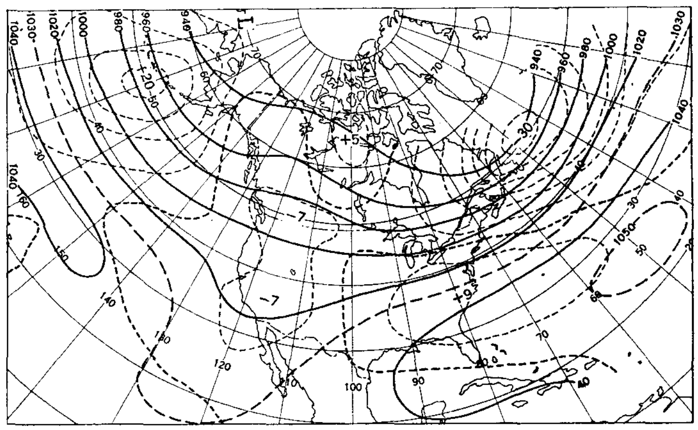

Figure 8.—Mean 700-mb. contours (solid lines) and anomalies (broken lines) for autumn 1941, a climatic pattern highly unfavorable for tropical cyclone penetration into New England.

The circulation patterns associated with a complete lack of tropical cyclones passing west of 65° W. at 40° N., i. e., the falls of 1939, 1941, 1947, 1949, 1951, and 1952, appear to be somewhat less homogeneous than the threat cases. Part of the reason for this is that different types of patterns may be unfavorable for genesis of West Indian tropical cyclones, may steer them beyond the confines of the area treated (40° W.) by the time they reach 40° N., or may steer them inland south of 40° N. to be rapidly dissipated over land. In all three cases the New England area remains invulnerable. In the fall of 1941, for example (fig. 8), the westerlies were anomalously strong over the Northeast coast and cyclones caught in this stream would probably be carried out to sea before reaching 40° N. However, the strong zonally-oriented positive anomaly extending from southeastern United States through Bermuda inhibited northward penetration and steered the cyclones westward into the Gulf of Mexico. Thus no tropical cyclones were recorded in the fall of 1941 passing 40° N. latitude in the western Atlantic.

Although the patterns of the minimum threat years seem to be less homogeneous than those of the maximum

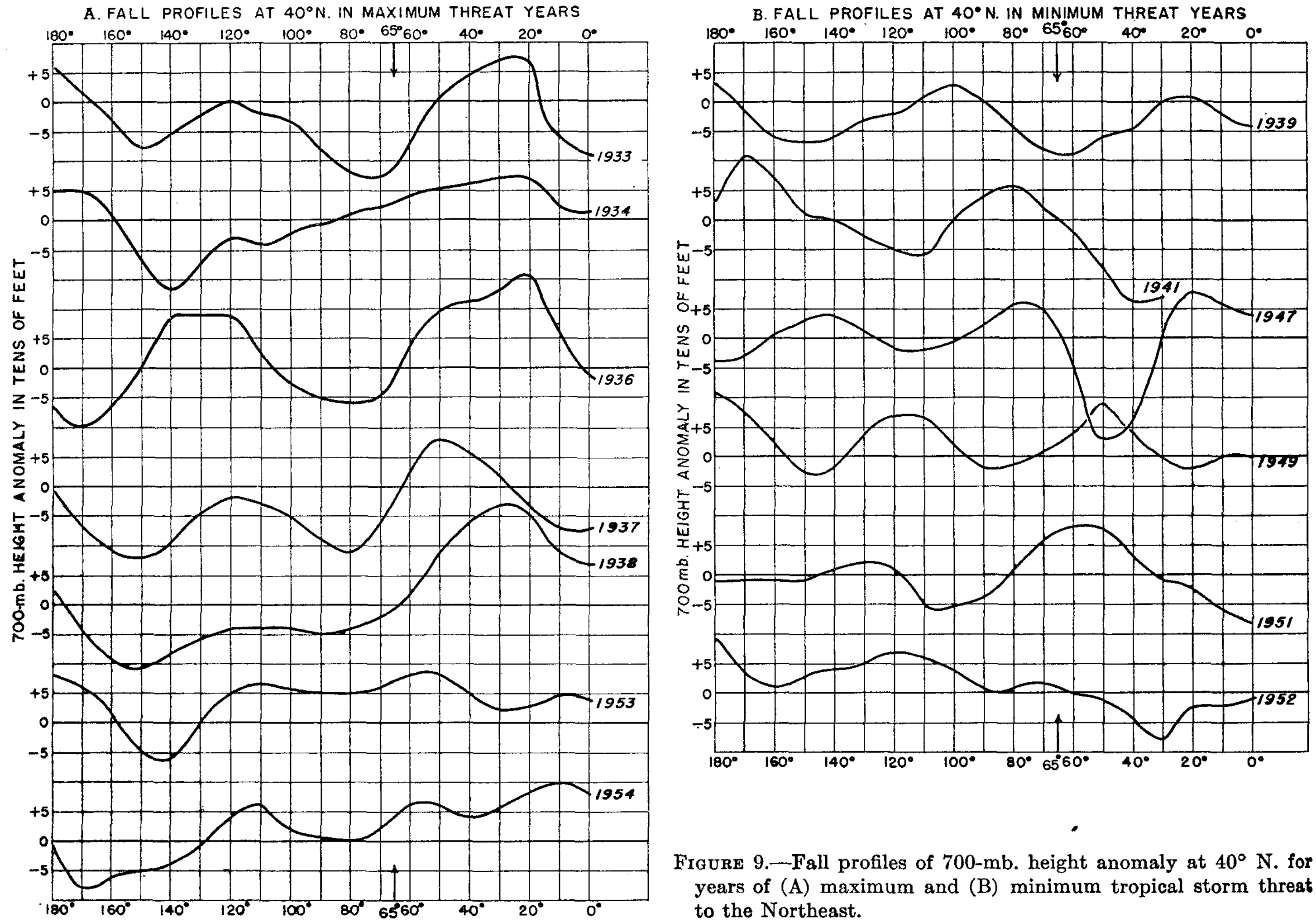

FIGURE 9.—Fall profiles of 700-mb. height anomaly at 40° N. for years of (A) maximum and (B) minimum tropical storm threat to the Northeast.

threat years their mean (fig. 3) displays some characteristic features. Comparing figures 2 and 3, the more striking differences are:

1. In the Atlantic in the minimum threat years a deep and extensive negative anomaly replaces the positive found in the maximum threat years.
2. A net positive anomaly exists over eastern United States rather than a negative.

Both the above features are unfavorable to northward steering by the Atlantic subtropical anticyclone.

3. The absence of a strong northwest Canadian positive anomaly makes less favorable the transport of cyclonic vorticity to encourage a trough in the Lake Region.

When superimposed upon the normal fall pattern (fig. 4) the net result of the mean anomalies of minimum threat years is a wave pattern of less amplitude than normal, particularly so compared to the mean of maximum threat years.

On the average, the years in which no September and October tropical cyclones passed westward of 40° N., 65° W. were also deficient in tropical storms over the entire western Atlantic (west of 40° W.). Thus in the seven no-threat years only about one-half the number of tropical cyclones per year (1.7) were observed to pass 40° N. as did in threat years (3.9). Apparently the patterns favoring meridional and thus farther than normal westward motion of these storms also favor cyclone development in the general area of the West Indies. This possibility has been mentioned in connection with the composite anomaly shown in figure 2, where one obtains the suggestion of deep polar troughs along the east coast which can penetrate to low latitudes.

Profiles of 700-mb. height anomaly along 40° N. for the maximum and minimum threat cases are reproduced in figure 9. In all the threat cases it will be noted that the anomalous gradient is directed from south to north at 65° W. However in the no-threat years the reverse gradient is present at this longitude on only four of the six cases, and the 1949 and 1951 profiles are quite the inverse of 1939, 1941, and 1947 profiles. In examining the more complete maps (not reproduced) it becomes clear that in 1951 the polar trough was entirely lacking in the east (note large positive profile anomaly) as was the positive anomalous area in Northwest Canada. This positive area often acts like a block to tropical storms, forcing them to skirt it by striking inland farther south and rapidly dissipating, or by moving off to sea without striking land at all. While the situation in 1949 is more difficult to diagnose, perhaps the most obvious fact to be derived from the maps is that the polar trough over the Lake region (note negative profile anomaly) was weak and did not penetrate into the Southeast.

3. INDICES OF VULNERABILITY

From the material reviewed thus far, it appears that the factors which differentiate between autumns posing considerable threat of tropical cyclones to coastal regions of northeastern United States and those which do not are as follows.

1. The threat years show a tendency to be associated with stronger than normal meridional components in the average planetary flow in mid-troposphere resulting in:
   (a) A deeper than normal trough just inside the United States coast, the negative anomaly penetrating into the Tropics.
   (b) Stronger than normal neighboring ridges in the western United States and especially Canada and in the central Atlantic.
   Both of these factors represent essentially an amplification of the pre-existing normal planetary wave pattern.
   (c) A Canadian anomaly pattern which favors increased north or northeast components north of the Lake region.
   (d) A deeper than normal Icelandic Low in about its normal position.
   (e) A deeper than normal trough off the west coast of United States (this is associated with the stronger than normal ridge over western United States).

2. On the other hand, the seasonal patterns associated with little or no threat to coastal regions of the Northeast are those which nullify in some way the steering effect of the eastern United States trough. This is usually effected by a marked positive anomaly here which is often associated with compensating negative anomalies over western United States and Canada and in the central Atlantic. The net effect results in a flatter than normal planetary wave pattern over North America and adjacent waters thereby providing for more eastward steering of any captured disturbances and also for reduced polar penetrations into the Tropics which may be important for the genesis of such storms. In the case of large positive anomalies near or over New England, tropical storms may be forced inland to the south and rapidly dissipate.

It is perhaps fascinating to design an index which relates the number of threats to the Northeast to the above-mentioned parameters.

Perhaps two of the simplest indices are the departure from normal of the 700-mb. height at 40° N., 50° W., which in effect measures the nature of the blocking ridge off the Atlantic coast, and the difference between the height anomalies between 60° W. and 80° W. along 40° N., which measures the anomalous steering gradient. From these plots, shown in figure 10, it is clear that part of the

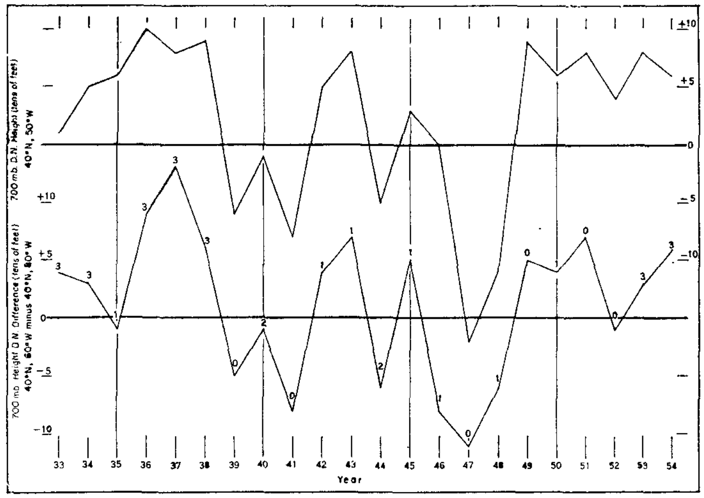

FIGURE 10.—(Upper curve) 700-mb. height anomaly at 40° N., 50° W. for successive autumns. (Lower curve) Difference in anomalous height gradient at 700 mb. between 60° W. and 80° W. at 40° N. Numbers beside curve refer to number of tropical storms passing west of 65° W. at 40° N.

information of the maps is captured by these indices. For example, about four times as many tropical storm threats occur with south-to-north anomalous gradients than with the reverse gradient between 60° W. and 80° W. The single value of the height anomaly at 40° N., 50° W. is similarly indicative. However, for an individual case like 1944 such simple indices fail.

Another index might incorporate the height anomaly in northwest Canada, say at 55° N., 105° W. (see fig. 2), along with the anomalies at 40° N., 80° W. and 40° N., 50° W. Giving equal weight to the three points, and considering the Canadian and Atlantic points contributing in a positive sense to threat when they are positive, but reversing the sign of the 40° N., 80° W. point, we can obtain summations which might also serve as a threat index. Table 2 summarizes the averages of this index for 0, 1, 2, and 3 storms passing west of 65° W. at 40° N.

Besides, twice as many threats occurred with indices above their average values for all seasons as with below average indices.

Apparently, even such crude and simple indices capture some of the large-scale features described above.

While further attempts to develop an objective index might improve the stratification it is believed that such an exercise would be unprofitable, because the trained synoptic meteorologist can probably evaluate the actual

TABLE 2.—*Average index (combination of height anomaly at three selected points—see text) for 0, 1, 2, and 3 threats (storms passing west of 65° W. at 40° N.)*

Number of threats	Average index	Number of cases
0	−4.0	6
1	7.0	5
2	13.3	4
3	18.7	7

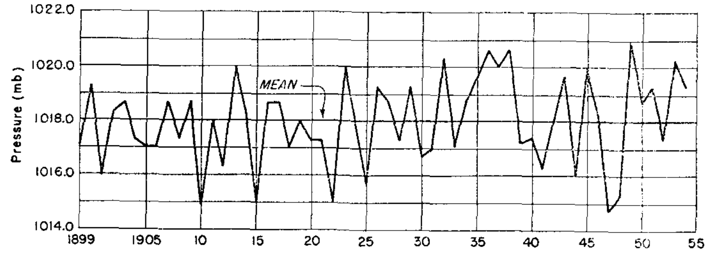

FIGURE 11.—Average sea level pressure at 40° N., 50° W. for the autumns (Sept., Oct., Nov.) of the years 1899–1954.

maps (which contain the complete data) more adequately than can a few numbers.

4. THE LONGER-PERIOD CLIMATIC FLUCTUATION

As Bergeron [8] has inferred, there is no reason why hurricanes, as well as temperature and rainfall, should not undergo long-period climatic fluctuations. The author [2] attempted to relate the increased vulnerability of late years along the Atlantic coast to the climatic warming there, showing that both the more northward steering of hurricanes and the abnormal warmth of recent winters were associated with a greater prevalence than normal of southerly flow with a maritime component in the lower troposphere.

Unfortunately it is not possible to extend the file of upper air charts beyond 1933, and therefore, the thesis advanced in this paper cannot be tested further. However, over ocean areas well removed from the continents it is well known to the synoptic analyst that there is a fairly good correlation in any one season between pressures at sea level and at 3 km. In monthly or seasonal means this correlation may run quite high. For example, for the 20 years 1933–38 and 1941–54 when good data were available, the correlation between seasonal means of sea level pressure and 700-mb. height at 40° N., 50° W. comes out to be 0.93. Inasmuch as this point captures some of the large-scale steering features described in this report (see fig. 2) a plot of the autumnal means for the period 1899 to date was made (fig. 11) using the historical map series [9] for the earlier years up to 1939. While one might fit a sloping upward trend line to these data it appears to the author that a somewhat different regime began around 1933. The difference shows up not so much in the means, which for 1933 to 1954 are 1018.4 mb. against 1017.7 mb. for the period from 1899 to 1932, but rather in the frequency of points above the long-period average. For example, while from 1899 to 1932 there were about an equal number of points lying above (47%) and below (53%) the average for the total period, after 1933 there were 66 percent above the average. It is also obvious that the frequency of high peaks has increased. It is unlikely that these differences are due to inadequate data of the earlier years of historical maps, for this area was reasonably well covered by reporting ships. Besides, such a trend is in keeping with the recent climatic warming along the east coast.

Thus we may be in a new climatic epoch as far as vulnerability of the Northeast to tropical storms is concerned. But before any predictions of years to come can be made there must be an understanding of what produces climatic fluctuations of the general circulation. We have not treated this vast problem in this paper, and in describing the anomalous features of the circulation which influence east coast vulnerability special care has been taken to avoid discussing ultimate causality. It could be, for example, that the strengthened Atlantic upper-level ridge which is associated with threat cases is in part a reaction from the well developed Icelandic trough, but as in all studies of long-period teleconnections it is not possible at present to disentangle the maze of entwined forces and resonant perturbations. Until this problem is solved, prediction of climatic fluctuations in hurricanes, as well as other elements, for more than a season in advance will probably enjoy little success. However, the moderate success obtained in 30-day forecasting can offer helpful clues.

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